euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Design of a 4 degrees of freedom decoupled monolithic compliant alignment mechanism for additive manufacturing

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Abstract

Optical systems require kinematic mounts to align the optical components relative to a light path during installation. Depending on the application and the exact type of optical component, these mechanisms may require up to six degrees of freedom (DOFs). An industry where such optical systems are important is the semiconductor industry where high precision alignment is required for production and inspection. Hysteresis, crosstalk and resonance vibrations result in reduced precision of existing devices. In this research a monolithic decoupled adjustable optical mount manufactured using additive manufacturing is proposed as a solution. A prototype was manufactured in grade 5 titanium using Laser Beam Melting. This prototype has 4 DOFs which can be adjusted in planar translational motion with a range of 1 mm and in rotational out of plane motion with a range of 1 mrad and a resolution of 10 µm and 10 µrad. Experiments show a first eigenfrequency of 610 Hz.

Keywords: compliant mechanism, optical alignment, kinematic mount, additive manufacturing

1. Introduction

Optical systems are applied in a growing part of industrial processes. In the semiconductor industry optical systems are required for both production and inspection of microchips. An optical system consists of a series of optical components which directs the light path going through the system. The decreasing size of details on microchips result in high requirements for the optical mounts which are used to align the optical components with the light path.

Conventional mechanisms [1] with sliding rigid bodies suffer from hysteresis and (virtual) play, which affects the adjustment resolution. Furthermore, coupling between DOFs [2] increases the adjustment iterations required by the operator. Finally, machines with optical systems used in industrial environments are subject to vibrations. Resonance should be prevented by realizing a high eigenfrequency of the mount.

In this paper the design of a monolithic optical mount with 4 decoupled DOFs and a high eigenfrequency suitable for additive manufacturing (AM) is proposed and evaluated. First, a monolithic mechanism would have no hysteresis and no play. Second, monolithic mechanisms have a high stiffness, by optimizing the design this property can exploited to achieve a high eigenfrequency. Finally, the design freedom of additive manufacturing can be used to design complex mechanisms with decoupled degrees of freedom.

The research approach will be discussed in section 2. Followed by the design of an optical mount in section 3. The prototype and experimental results will be evaluated in section 4. Finally, the conclusions are given in section 5.

2. Methodology

The design objective is a 2-inch concave mirror mount with an adjustment mechanism. The mechanism with 4 adjustable DOFS: 2 orthogonal translations in plane of the mirror and two tilting rotations out of plane, with adjustment ranges of 1 mrad and 1 mm with a resolution of 1 µm and 10 µrad, respectively. The axes of rotation of the tip and tilt rotations pass through the optical centre of the mirror. Since the requirements for different applications will be different a transmission mechanism is added for each adjustable DOFs.

2.2. Eigenfrequency optimization

The eigenfrequency of the optical mount increases with the stiffness of the system. The maximum stiffness is limited by the yield strength of the flexures in the mechanism. By optimizing the flexures an optimal eigenfrequency can be achieved. By measuring the acceleration and applied vibrational force the frequency response can be determined from which the first eigenfruencies can be extracted.

2.3. Design for additive manufacturing

Additive manufacturing gives more design freedom compared to conventional manufacturing methods, but sometimes requires support structures which result in higher post-processing costs. Support structures are not required when the design has no floating features. Circular or tilted overhanging features can be used when the diameter and overhang angle are limited. The overhang angle is the angle between the build direction and the downfacing surface.

3. Optical mount design and actuation

The proposed design in shown in figure 1. This adjustment mechanism is divided in 2 stages. The first stage has parallel adjustments in X and Y translational and is suspended by compliant parallelogram structures which act as prismatic joints [3]. In series with this parallel stage is the parallel stage holding the mirror which can be rotated about the X and Y axes using a compliant mechanism based on a decoupled spherical 5 bar mechanism [4]. The DOFs are actuated using adjustments screws with a pitch of 80 threads per inch (TPI) for the translations and 508 TPI for the rotations.

3.1. Design of flexures

There are two kinds of flexures used in this design: elastic hinges and leaf springs. The leaf springs can be described by the length, width and thickness and the elastic hinges by the diameter of the circular notch, the minimum thickness between the notches and the constant width of the hinge. The flexures are optimized for maximum stiffness while bounded by the maximum yield stress when the maximum displacement is applied. This results in the parameters shown in tables 1 and 2.

Table 1. Parameters of leaf springs

Leaf spring	Length [mm]	Width [mm]	Thickness [mm]
1-4	25	20	1
5-8	15	7	1
9,10	10	20	1

Table 2. Parameters of elastic hinges

Elastic hinge	Diameter [mm]	Width [mm]	Thickness [mm]
11-18	8	20	1
19-21	8	3	3

3.2. Transmission sensitivity and resolution

The transmission sensitivity of the translational DOFs is equal to $\frac{L_1}{L_2} = 1$ as shown in figure 1. For the rotational DOFs the transmission turns the translational actuation into a rotation following $\alpha = \sin^{-1}\frac{u}{L_3}$, where α is the rotation, u is the input displacement and L_3 is the length of the lever. For small rotations the transmission sensitivity will be equal to L_3 which is 2 mm/rad. The smallest rotation a human operator could make with an adjustment screw is 1° [5]. This results in an adjustment resolution of 1.06 µm for the translational adjustments and 6.94 µrad for the rotational adjustment.

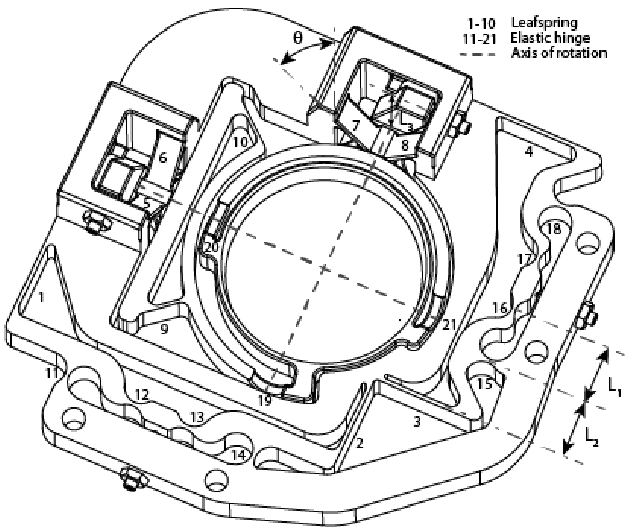

Figure 1. Drawing of the optical mount with numbered flexures and transmission parameters.

4. Results

The optical mount is manufactured in Grade 5 Titanium using Laser Beam Melting (LBM) as shown in figure 2. Visual inspection shows a good result without any defects, only some surface roughness as would be expected from additive manufacturing. To measure the frequency response the mechanism is excited using an electrodynamic shaker and the excitation force is measured using a force sensor. The resulting displacement is measured with a scanning laser doppler vibrometer which measures the displacements over the entire surface of the optical mount. The resulting frequency response function in shown in figure 3. Examination of the eigenmodes shows that the first peaks up to 50 Hz result from rigid body modes. The peaks around 360 Hz result from vibrations of the levers which actuate the translational stage. The peak at 610 Hz is the first eigenfrequency which results in resonance vibration normal to the mirror. Other eigenfrequencies up to 1 kHz appear at 670, 840 and 940 Hz.

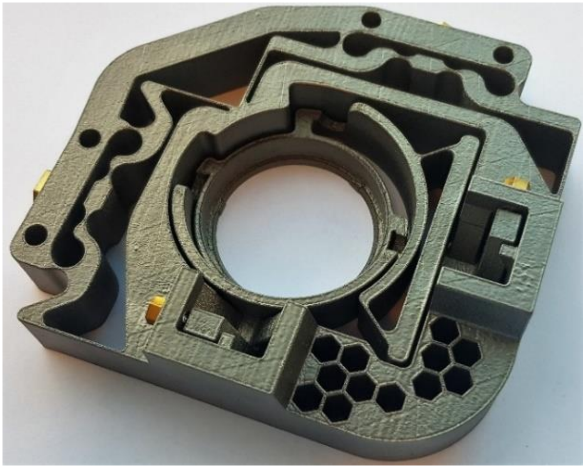

Figure 2. a picture of the printed optical mount with some surface roughness as a result from printing and small irregularities on the tilted leaf springs.

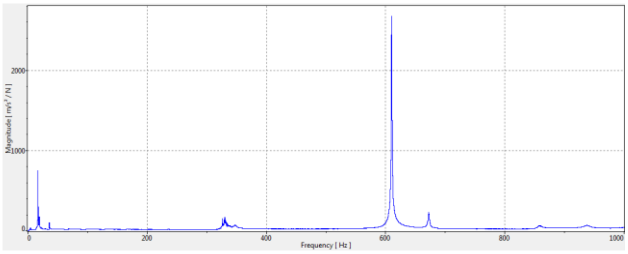

Figure 3. The magnitude of the frequency response plotted over the frequencies between 0 and 1 kHz.

5. Conclusion

A new design for an optical mount with 4 decoupled degrees of freedom was proposed considering the advantages of additive manufacturing. The prototype, manufactured from grade 5 titanium using Laser Beam Melting, showed to be a functional adjustable optical mount. Experiments have shown a first eigenfrequency of 610 Hz which is more than sufficient for the current machines in the semiconductor industry. From these results it is concluded that additive manufacturing is a viable production method for monolithic adjustable precision mechanisms. Future research includes the evaluation of other prototypes to examine the effect of variations of the flexure designs and also the crosstalk between the degrees of freedom of the mechanism.

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